

# Physics Goals and Status of JEM-EUSO and its Test Experiments

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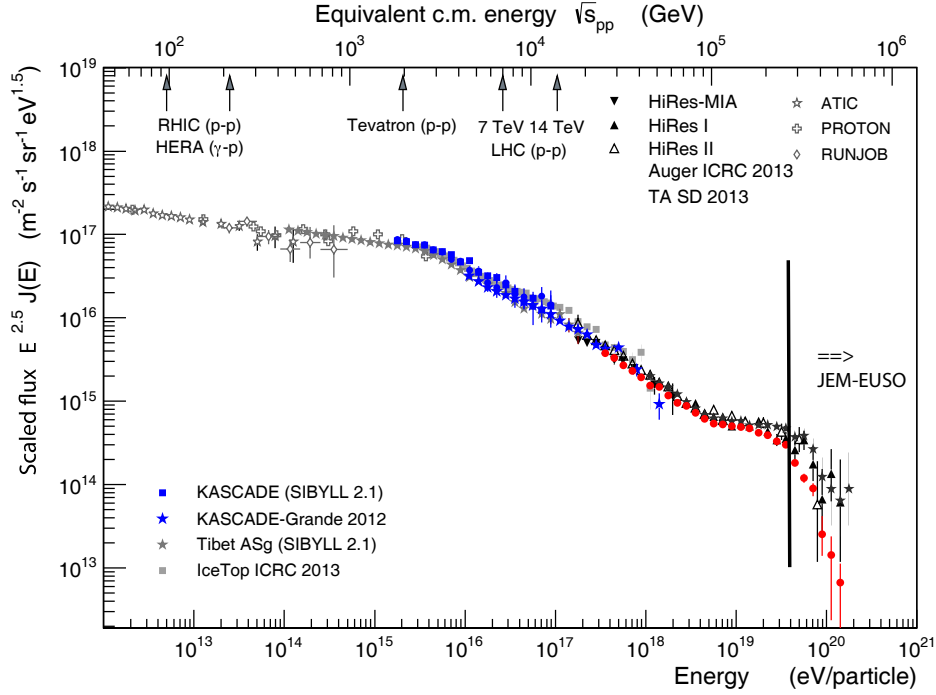
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**Abstract.** The JEM-EUSO mission aims to explore the origin of the extreme energy cosmic rays (EECRs) through the observation of air-shower fluorescence light from space. The superwide- field telescope looks down from the International Space Station onto the night sky to detect UV photons (fluorescence and Cherenkov photons) emitted from air showers. Such a space detector offers the remarkable opportunity to observe a huge volume of atmosphere at once and will achieve an unprecedented statistics within a few years of operation. Several test experiments are currently in operation: e.g., one to observe the fluorescence background from the edge of the Atmosphere (EUSO-Balloon), or another to demonstrate on ground the capability of detecting air showers with a EUSO-type telescope (EUSO-TA). In this contribution a short review on the scientific objectives of the mission and an update of the instrument definition, performances and status, as well as status of the test experiments will be given.

## 1. Introduction

The region of cosmic rays of the highest energies, i.e. the Extreme Energy Cosmic Rays - EECR, of the wide spanning cosmic ray energy spectrum is the one least explored. This is natural as the flux of such particles reaching Earth is extremely low. In addition to the low statistical accuracy, the existing measurements disagree in their flux by a surprisingly large amount (see Fig. 1).

The origin of the differences is still not fully understood and several causes may play a role. One reason could lie in the fact that the energy reconstruction is limited by our current theoretical understanding of extensive air showers (EAS) [1]. These showers are generated by interaction of the impinging cosmic particle with the Atmosphere. The products of this are measured with detectors of large exposure and the data is interpreted in terms of the arrival direction, energy and mass of the primary particle. The features of the first interaction (cross-sections and multiplicity distributions of secondaries) as well as partly the kinematic features (extreme forward direction) of interactions at all energies relevant for the shower development are not well measured by accelerators. Hence, extrapolations are used in simulating the EAS leading to different interpretations if different hadronic interaction models or different observables are used. Another cause could be that the two main experiments at the highest energies (Pierre Auger Observatory [2] and Telescope Array [3]) are located at different hemispheres and therefore, look at different regions of the sky. Several theories suggest that the EECR stem from astronomically nearby ( $< 100$  Mpc) Active Galactic Nuclei, where it is well known that the distributions of those AGNs are not uniform over the sky [4].



**Figure 1.** The all-particle spectrum of cosmic rays as measured by various experiments. Largest uncertainties are in the region of the highest energies: the target of the JEM-EUSO mission.

For future experiments, large efforts have to be made to reach significantly higher statistics in measurements as well as a coverage of the whole sky. Both require a much higher exposure than that of existing experiments.

The Extreme Universe Space Observatory (EUSO) (Fig. 2) at the Japanese Module (JEM) of the International Space Station (ISS) is the first space mission devoted to the scientific research of EECR [5–8].

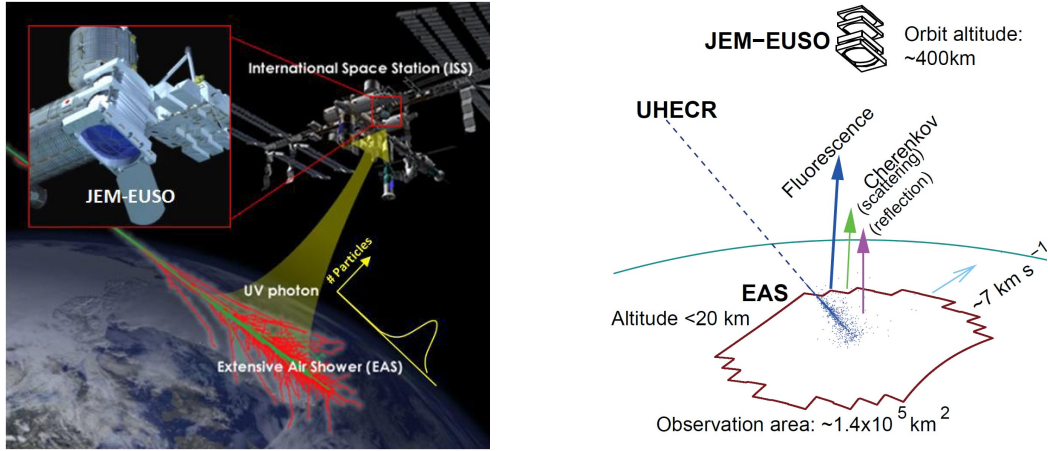
## 2. JEM-EUSO

### 2.1. Scientific Goals

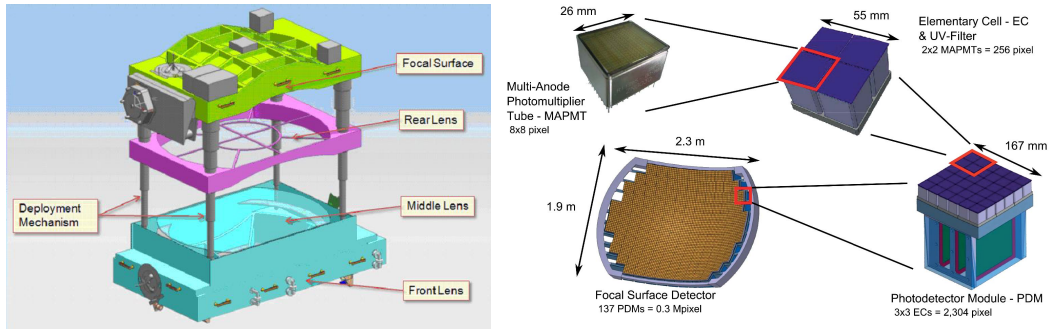
Main goal is the exploration of the Universe through the detection of the extreme energy cosmic rays and neutrinos by looking downward from the ISS to detect the fluorescence light of extensive air-showers that they generate in the Earth’s atmosphere (Fig. 2).

The main scientific objective is astronomy and astrophysics through the particle channel. This requires to identify the sources of cosmic rays by the reconstruction of the arrival direction and energy spectra with a high collecting power, beyond any other previous or planned experiment so far. In addition, exploratory objectives were defined [9]. This leads to the following physics program of JEM-EUSO:

- (i) astronomy and astrophysics through the particle channel at  $E > 5 \times 10^{19}$  eV;
- (ii) the detection of extreme energy gamma rays;
- (iii) the detection of extreme energy neutrinos;
- (iv) exploratory studies of the galactic magnetic fields;
- (v) fundamental physics studies (e.g. Lorentz invariance tests) at extreme energies;



**Figure 2.** Left: Principle of the JEM-EUSO mission to detect extreme energy cosmic rays via the fluorescence emission of extensive air showers in the Atmosphere. Right: Schematic view of the JEM-EUSO mission: EASs generate fluorescence light that is emitted isotropically as well as Cherenkov light emitted in forward direction. The latter is also scattered and reflected and can reach the aperture of the telescope.



**Figure 3.** Conceptual view of the JEM-EUSO telescope with its three lenses (left panel). Schematic view of the focal surface and its components of the JEM-EUSO mission (right panel).

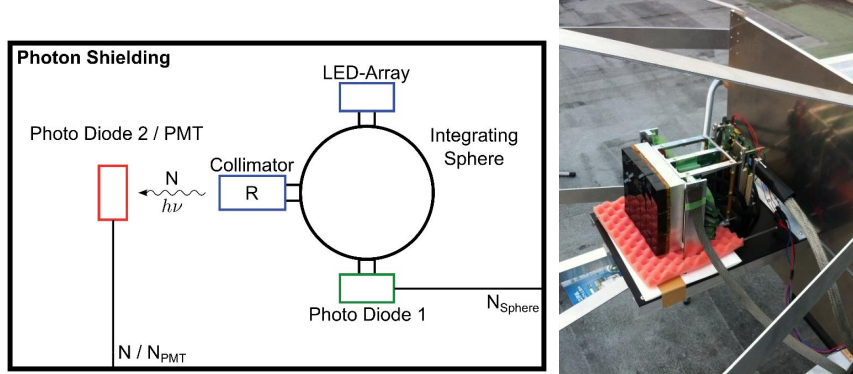
(vi) global survey of nightglows, plasma discharges, lightning, meteors and other terrestrial transient sources in UV light.

The last one is possible due to the fast UV-light monitoring of the entire Atmosphere, which was never performed before.

Detailed simulations have shown that with three years of operation, JEM-EUSO will achieve a statistics of 100 events above  $10^{20}$  eV and that with these events, if exists, nearby sources (even with a heavy dominant elemental composition at those energies) will be identified [10].

## 2.2. Instrument

The JEM-EUSO instrument [8, 11] consists of the telescope, the focal surface, a monitoring system for the atmospheric conditions, and a calibration system. In addition, there will be support and calibration systems on ground as well as at the ISS. The telescope (Fig. 3) consists of four main parts: collecting optics with 3 Fresnel lenses, a focal surface detector, electronics and a structure. JEM-EUSO constitutes a  $\mu$ s-fast and highly pixelized digital camera with a diameter of about 2.5 m and a  $\pm 30^\circ$  wide field of view. It works in the near-UV wavelength



**Figure 4.** Left: Sketch of the calibration stand for photo sensors. Right: first fully assembled Photo Detector Module (PDM) for JEM-EUSO prototype experiments.

(290 – 430 nm) and enables a single-photon counting.

The focal surface will consist of 4932 64-channel multianode photomultipliers from Hamamatsu. They will be organized in elementary cells of 4 PMs each and in 137 photo detection modules (PDM) of 9 elementary cells each. The focal surface (Fig. 3) comprises therefore more than 300,000 pixels in total. The electronics processes triggers for air-shower or other transient events in the Atmosphere and send necessary data to the ground for further analysis.

The optics with three Fresnel lenses focuses the incident UV photons onto the focal surface with an angular resolution of  $0.07^\circ$ .

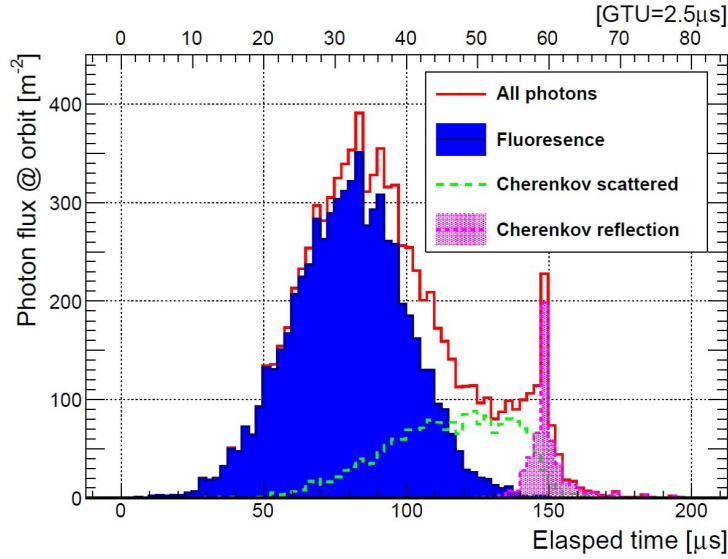
The Atmospheric Monitoring System (AMS) [12] consists of an infrared camera [13] and a LIDAR (Light Detection And Ranging) system, both monitoring the Earth’s atmosphere continuously inside the FoV of the JEM-EUSO telescope. A measurement of clouds top heights with an accuracy better than 500 m will be possible.

### 2.3. Calibration

For fluorescence detection of cosmic rays it is essential to calibrate the detector pre-flight with utmost precision and to monitor the performance of the detector throughout the whole mission time. For that purpose a calibration stand on-ground was built to measure precisely the performance of Hamamatsu 64 pixel MAPMTs that are planned to be used for JEM-EUSO (Fig. 4). It consists of a photon shielding, a uniform light source and readout electronics for the MAPMTs. The uniform light is available thanks to an integrating sphere and the light intensity is monitored in real-time by a NIST-calibrated photo diode attached to the sphere. To investigate the suitability of alternative detector devices, further research is done with state-of-the-art silicon photomultipliers (SiPMs). These will also be tested in the calibration stand and their performance can be compared to conventional photomultiplier tubes. A designed inflight calibration system measures continuously the efficiencies of the optics, the focal surface detector, and the data acquisition electronics [14, 15].

### 2.4. Performance of JEM-EUSO

Figure 5 shows a typical longitudinal profile of an EAS at the pupil of the telescope. Simulations including the transmission losses of the optical system, the efficiency of the focal surface, as well as the rate of background photons show that JEM-EUSO reaches almost full efficiency already at energies around  $3 \cdot 10^{19}$  eV for a restricted subset of events, and full aperture at energies  $E > 5 - 6 \cdot 10^{19}$  eV. The annual exposure of JEM-EUSO at  $10^{20}$  eV will exceed by one order



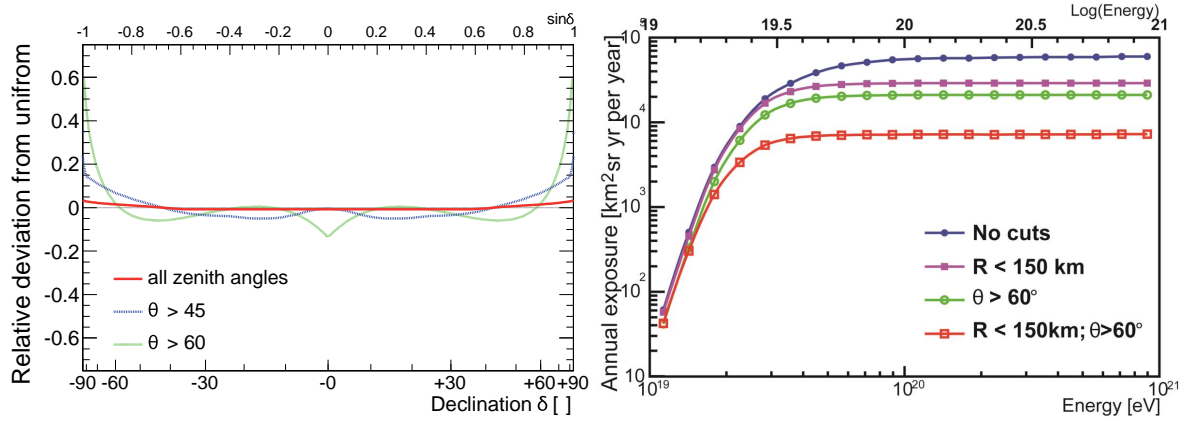
**Figure 5.** Arrival time distribution of photons at the pupil of the telescope per  $\text{m}^2$  from a simulated high-energy EAS in case of a clear atmosphere.

of magnitude the level presently reached by ground-based observatories. For clear atmospheric conditions a reconstruction of the shower geometry and primary energy with good accuracy, as well as a rough estimate of the shower maximum will be possible [16]. In presence of optically thin clouds at high altitudes, often also categorized as cirrus, most of the EAS photons penetrate the layer of clouds and are attenuated only partly. This may lead to a reconstruction with a lower energy, however, the situation can be taken into account as the clouds are monitored by the AMS and the information is known for each triggered EAS. The geometry of the shower axis can still be properly determined by the analysis of the angular velocity of the EAS signal.

One big advantage of JEM-EUSO will be the uniform full sky coverage due to the ISS orbit (Fig. 6, left). JEM-EUSO will be the first experiment to be able to take data of EECRs for both hemispheres to build a full sky map. This will lead to anisotropy studies and identification of sources and source regions of high-energy cosmic rays which is not possible with ground-based observatories.

The second advantage of the JEM-EUSO mission - compared to existing cosmic ray experiments using the fluorescence technique - is the big observation area on ground and therefore the big detector volume. This will enhance the statistics for UHECR events that are expected with a rate of one event per century per steradian per kilometer squared. JEM-EUSO will have a large observation area in nadir mode (studied here, Fig. 6, right panel) and even a roughly ten times bigger one in tilt mode (not yet fully explored, but the design enables the option to tilt the entire instrument at the ISS to have a larger coverage on ground).

JEM-EUSO triggers on the UV light from EAS, measures the intrinsic luminosity of each EAS near its maximum and accurately reconstructs the EAS path so that the arrival direction of the initiating EECR can be reconstructed. Detailed studies [9] indicate that for 68% of the events the arrival direction can be reconstructed to better than  $2.5^\circ$ . Regarding the energy reconstruction, at the current status of development of the reconstruction algorithms, proton showers are reconstructed in clear-sky conditions with a typical energy resolution  $\Delta E/E$  of  $\approx 25\%$  (20%) at energies around  $4 \cdot 10^{19}$  eV ( $10^{20}$  eV). In addition, our still preliminary results indicate that the  $X_{max}$  resolution can be better than  $70 \text{ g/cm}^2$  for  $E > 10^{20}$  eV in the central



**Figure 6.** Left: Relative deviation from uniformity of the aperture as a function of sine of declination. The curves show the cases for a selection of events with different zenith angle. Right: Annual exposure of JEM-EUSO (ISS at 400 km) for the full FoV and for the case of extremely high quality cuts applied to the data. For the most stringent cuts, the threshold is low enough for an overlap with ground based experiments with good statistics. Plots adapted from [9].

part of the FoV. With 0.1 - 1 million km<sup>2</sup> sr exposure and the uniform coverage of the full sky, JEM-EUSO will observe all possible source directions at least within several hundred Mpc and will make possible the (i) identification of sources with unprecedentedly high statistics by arrival direction analysis and (ii) the measurement of the energy spectra from individual sources to constrain the acceleration or the emission mechanisms.

### 3. Test Experiments

On the way to the full instrument ready for launch to the ISS, several test or pathfinder experiments are needed and currently under development or in operation.

A PDM (photon detection module with 2304 pixels, see Figs. 3 and 4) can be seen as an independent unit, where one of which are or will be used for most of the test experiments. However, new optical systems are adapted for the respective purpose.

- **EUSO-Balloon:** EUSO-Balloon [17] will serve as a demonstrator for technologies and methods featured in the space instrument (Fig. 7, right panel). This balloon-borne instrument points towards the nadir from a float altitude of about 40 km. With its Fresnel optics and PDM, the instrument monitors a 12 by 12 degree wide field of view. Key objectives are among others the full-scale end-to-end test of the JEM-EUSO technique, the experimental determination of the effective UV background below 40 km, ground based calibration systems, and, the observation of the first UV-image of an EAS looking down on the Earth's atmosphere. The flights are handled by the balloon division of the French Space Agency CNES. A first flight was performed on August, 25, 2014 at Timmins, Canada. 5 hours of valuable data from the PDM, from the installed infrared camera, as well as Laser pulses sent by a helicopter accompanying the full flight are presently being analysed.
- **EUSO-TA:** Also important information on the capabilities of the full instrument will be provided by EUSO-TA [18], which is a ground-based telescope formed by one PDM (identical to the PDM of EUSO-Balloon) and two Fresnel lenses, which are prototypes of those foreseen in JEM-EUSO. EUSO-TA will be located at the Telescope Array (TA) [3] site in Utah, USA (Fig. 7, left panel). The instrument will measure the UV light in the





**Figure 7.** Left: photo of the EUSO-TA installation in the front of the Telescope Array fluorescence detector in Utah, US. Right: photo of the EUSO-Balloon payload (with floating devices) just before the launch in August 2014 in Timmins, Canada.

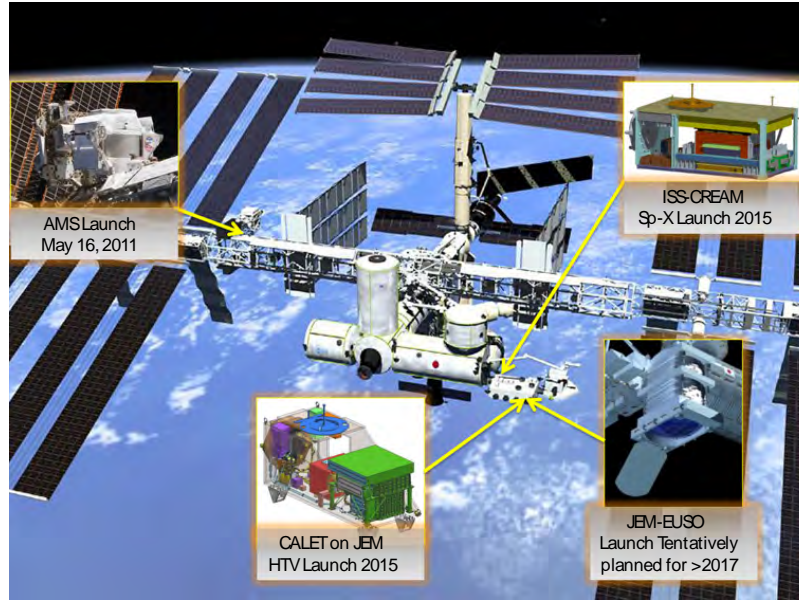
Atmosphere in its  $\pm 4$  degrees FoV, will be triggered by the fluorescence detectors of TA, and will make use of the LIDAR and the Electron Light Source of TA. The aims are to obtain an end-to-end calibration of the prototype telescope, and an inter-calibration with the fluorescence detector of TA. Everything is prepared to start the measurements in early 2015.

- **K-EUSO:** Currently, the collaboration considers a cooperation with the Russian project KLYPVE. KLYPVE [19] is a mirror based fluorescence telescope foreseen to be installed at the Russian segment of the ISS. Despite its smaller size, KLYPVE could be the first experiment detecting EAS from space. Combined with a Fresnel lens and a JEM-EUSO type focal surface the exposure and quality of the experiment could be considerably improved. However, due to limitations in space and weight, the exposure of the baseline JEM-EUSO design probably can not be reached.
- **Mini-EUSO:** Another project is Mini-EUSO, a small prototype experiment (one PDM and a two-25cm-diameter Fresnel-lens system) foreseen to operate inside the ISS for an observation of the UV emission from the night-Earth through an UV-window. This instrument would map for the first time the Earth in UV, and could study atmospheric phenomena and bio-luminescence at Earth as well as meteors.
- **SiPM-EUSO:** The collaboration has also started to evaluate if SiPM can replace the heavy and expensive Multianode PMT's presently in use. Designing and manufacturing an R&D early prototype of a SiPM based PDM is under study for the use in the test experiments.

#### 4. Outlook

JEM-EUSO is planned as a three to five year mission, where initially the launch was foreseen in 2017. Due to financial reasons this will not be possible. However, the JEM-EUSO collaboration continues the efforts to improve the baseline design and the capabilities and sensitivity of such an instrument with the aim to launch it to space at a later opportunity. Still the idea lives on of a comprehensive, virtual wide-range Cosmic Ray Observatory in space, like outlined by Vernon Jones from NASA, e.g. (Figure 8).

The various test and pathfinder experiments presently under construction or in operation will provide more information and details on the capabilities of a space instrument like JEM-EUSO.



**Figure 8.** Illustration of four cosmic ray instruments on the ISS, which would comprise complementary studies of a wide field in cosmic ray physics. Picture taken from [20].

### Acknowledgments

Supported by the ‘Helmholtz Alliance for Astroparticle Physics HAP’ funded by the Initiative and Networking Fund of the Helmholtz Association.

### References

- [1] d’Enterria D *et al.* 2011 *Astropart. Phys.* **35** 98
- [2] Abraham J *et al.* (Pierre Auger Collaboration) 2008 *Phys. Rev. Lett.* **101** 061101
- [3] Abu-Zayyad T *et al.* (Telescope Array Collaboration) 2013 *Astropart. Phys.* **39** 109
- [4] Véron-Cetty M-P and Véron P 2006 *Astron. Astrophys.* **455** 773
- [5] Ebisuzaki T *et al.* 2008 *Nucl. Phys. B (Proc. Suppl.)* **175** 237
- [6] Takahashi Y *et al.* 2009 *New J. Phys.* **11** 065009
- [7] Casolino M *et al.* (JEM-EUSO Collaboration) 2011 *Astrophys. Space Sci. Trans* **7** 477
- [8] Casolino M *et al.* (JEM-EUSO Collaboration) 2014 *Exp. Atron.* DOI 10.1007/s10686-014-9418-x
- [9] Adams J *et al.* (JEM-EUSO Collaboration) 2013 *Astropart. Phys.* **44** 76
- [10] Rouillé d’Orfeuill B *et al.* 2014 *Astron. Astrophys.* **567** A81
- [11] Kajino F *et al.* 2010 *Nucl. Inst. Meth. A* **623** 422
- [12] Toscano S *et al.* (JEM-EUSO Collaboration) 2014 *Exp. Atron.* DOI 10.1007/s10686-014-9378-1
- [13] Morales de los Ríos J A *et al.* (JEM-EUSO Collaboration) 2014 *Exp. Atron.* DOI 10.1007/s10686-014-9402-5
- [14] Karus M *et al.* (JEM-EUSO Coll.) 2013 *Proc. 33rd ICRC, Rio de Janeiro* **ID0545** arXiv:1307.7071
- [15] Sakaki N *et al.* (JEM-EUSO Coll.) 2013 *Proc. 33rd ICRC, Rio de Janeiro* **ID0546** arXiv:1307.7071
- [16] Fenu F *et al.* (JEM-EUSO Coll.) 2011 *Proc. 33rd ICRC, Beijing* **3** 116 arXiv:1204.5065
- [17] von Ballmoos P *et al.* (JEM-EUSO Coll.) 2013 *Proc. 33rd ICRC, Rio de Janeiro* **ID1171** arXiv:1307.7071
- [18] Casolino M *et al.* (JEM-EUSO Coll.) 2013 *Proc. 33rd ICRC, Rio de Janeiro* **ID1213** arXiv:1307.7071
- [19] Panasyuk M *et al.* 2014 these proceedings
- [20] Jones W V 2014 *Braz. J. Phys.* **44** 534